The Concept of a Stare-Mode Astrometric Space Mission

N. ZACHARIAS AND B. DORLAND

US Naval Observatory, 3450 Massachusetts Avenue, NW, Washington, DC 20392; nz@usno.navy.mil, bdorland@usno.navy.mil

ABSTRACT.   In this paper, we introduce the concept of a stare-mode astrometric space mission. The traditionally accepted mode of operation for a mapping astrometric space mission is that of a continuously scanning satellite, such as the successful *Hipparcos* and planned *Gaia* missions. With the advent of astrometry missions mapping out stars to 20th magnitude, the stare mode has become competitive. A stare mode of operation has several advantages over a scanning mission if absolute parallax and throughput issues can be successfully addressed. Requirements for a stare-mode operation are outlined here. The mission precision for a stare-mode astrometric mission is derived as a function of instrumental parameters, and examples are given. The stare-mode concept has been accepted as a baseline for the NASA road map study of the *Origins Billions Star Survey* (*OBSS*) mission and the proposed *Milliarcsecond Pathfinder Survey* (*MAPS*) microsatellite project.

1. INTRODUCTION

The current paradigm for a mapping astrometric mission is a scanning satellite with two fields of view (FOVs), which are separated by a large angle of ~50° to 100°. This concept was first introduced by P. Lacroute (Lacroute 1982). The two FOVs are imaged onto the same focal plane; thus, relative position measurements of stellar images in the focal plane allow wide-angle measurements on the sky. This observing strategy leads to a well-conditioned least-squares problem to solve for absolute parallaxes. For any small area in the sky, the parallax factor (van de Kamp 1967) is about the same, leading to large correlations in a global solution for absolute parallaxes based on stellar all-sky observations of small-angle astrometric measurements alone.

This concept of two FOVs separated by a "basic angle" worked very well for the ESA *Hipparcos* mission (ESA 1997). It has also been adopted for the planned ESA *Gaia* mission (ESA 2000), the canceled *FAME* mission (Johnston 2003), and for the unfunded *DIVA* (*Double Interferometer for Visual Astrometry*; Röser 1999) and *AMEX* (*Astrometric Mapping Explorer*; Gaume & Johnston 2003) missions. Another advantage of this concept is the almost 100% efficiency in data collection, with continuous observations in time-delayed integration (TDI) mode using charge-coupled devices (CCDs). Together with the success of the *Hipparcos* mission, the scanning concept has been adopted as the optimal concept for a mapping astrometric mission.[1] However, going to much higher accuracies and fainter limiting magnitudes with access to galaxies and quasars justifies

a second look at the basic operation principle and possible alternatives.

The stare-mode concept for an all-sky mapping astrometric space mission is presented here; it requires only a single FOV and operates differentially. This is contrary to the quasi-absolute, large-angle measurement principle that uses two FOVs for a scanning mission. A stare-mode operation with two FOVs is technically feasible. However, this approach would avoid only some of the issues raised here for a scanning mission and is not discussed further.

In § 2 the disadvantages of scanning astrometric space missions are presented, and in § 3 the stare-mode concept is presented as an alternative to overcome these problems, stressing the requirements that need to be met in order to be a viable option. In § 4 mission precision and other relevant mission parameters are derived from instrumental and basic input parameters. Section 5 discusses some realistic examples for small- and large-scale astrometric missions, based on this stare-mode concept. The *Origins Billions Star Survey* (*OBSS*; Johnston et al. 2004) study adopted as a baseline the proposed stare-mode operation principle. The *OBSS* is a NASA-sponsored investigation for NASA road map planning. The *OBSS* study report was submitted in 2005 May (Johnston et al. 2005), and more details are given elsewhere (Johnston et al. 2006).

2. DISADVANTAGES OF A SCANNING ASTROMETRIC MISSION

The main issues with a scanning astrometric mission such as *Hipparcos* and *Gaia* are as follows:

1. *Basic angle stability.*—In the 1 mas regime (*Hipparcos*), the basic angle stability was already technologically challenging. For 10 μas, this becomes a major cost driver and a primary

---

[1] The *Space Interferometry Mission* (now the rescoped *SIM PlanetQuest*) is also a dedicated astrometric mission; however, it operates on a totally different concept (interferometry) and can observe only a very limited number of preselected targets.

1. REPORT DATE **OCT 2006**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**	
4. TITLE AND SUBTITLE **The Concept of a Stare-Mode Astrometric Space Mission**			5a. CONTRACT NUMBER
			5b. GRANT NUMBER
			5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)			5d. PROJECT NUMBER
			5e. TASK NUMBER
			5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Library U.S. Naval Observatory 3450 Massachusetts Avenue, N.W. Washington, DC 20392-5420**			8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**			
13. SUPPLEMENTARY NOTES			
14. ABSTRACT			
15. SUBJECT TERMS			

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT **SAR**	18. NUMBER OF PAGES **9**	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**			

source of systematic errors. For example, the *Gaia* design (ESA 2000) requires passive temperature stability in the micro-Kelvin regime and an active metrology system.

2. *Two apertures separated by a large angle*.—This has the advantage of direct, wide-angle measurements, but on the other hand, it becomes a problem with respect to image confusion and crowding in the focal plane, as well as instrument complexity, due to the tough engineering requirement of having no significant beam walk to make use of this concept as intended. The complexity of beam-splitter hardware is costly.

3. *CCD versus CMOS*.—The scanning concept relies on driving focal plane detectors in TDI mode, which can only be accomplished with CCDs. Complementary metal oxide semiconductor (CMOS) detectors (or hybrid detectors), which show promise for future applications, may be better suited for space applications, being radiation hard. In addition, CMOS pixels do not spill charge ("blooming") and thus are inherently better suited for bright-star astrometric observations and for spanning a very large dynamic range, even when small pixel sizes are considered. Current CCD technology supports various antiblooming features. However, the most effective lateral antiblooming becomes increasingly problematic for CCDs as the pixel size decreases, effectively becoming impractical at the 8 μm size.

4. *Scanning restrictions*.—The scanning mission is limited to a specific scanning law. No target of opportunity can be observed. In addition, the integration time is fixed (optimized for uniform scanning speed) and is typically relatively short (i.e., a few seconds), due to other constraints, forcing the mission to use a large aperture to reach faint limiting magnitudes. Slower scanning is undesirable for satellite stability and for other reasons. Large apertures drive focal length, mass, and cost and make access to bright stars problematic. The scanning law and the Sun exclusion angle lead to an uneven sky coverage, typically varying the average astrometric parameters for the mission precision by a factor of 2 as a function of ecliptic latitude. No specific target areas can be observed with a precision other than that dictated by the scanning law. The temporal cadence of observations has no flexibility.

5. *Image smearing*.—The spacecraft angular momentum vector needs to precess in order to produce an all-sky survey. The continuous precession results in image smearing. Remaining differential distortions over the field of view add to image smearing. Elongated or generally asymmetric image profiles increase the astrometric errors, including both random and systematic errors.

6. *Jitter*.—Small nonuniformities of the scanning (spacecraft jitter) cause changes in the image profiles as a function of time. The TDI mode does not integrate all stars in a given field simultaneously; thus, different stars observed almost at the same epoch (same FOV) are affected differently, leading to positional offsets that need to be modeled or else can cause additional random and systematic errors.

7. *One-dimensional data*.—The scanning operation gives only one-dimensional measurements at high precision. This has some advantages (e.g., simple profile fit) but has significant disadvantages in the later stages of the data reduction and global astrometric reconstruction (e.g., error propagation issues, mixing with instrumental effects, and attitude control). In addition, for many applications (parallaxes, planet detections), the one-dimensional observations will quite often (nearly 50% of the time) be along the "wrong axis," while two-dimensional data give results for any projection angle for any single observation.

8. *Downlink*.—It is difficult to use a steerable high-gain antenna (HGA) to achieve a high downlink rate from an L2 orbit. In order to achieve comparable data rates (~30 Mbytes s^{-1}), a spinning satellite must either be positioned close to Earth or employ a dedicated relay satellite equipped with a directional HGA, at significant additional cost to the program. A stare-mode satellite could be equipped with an HGA.

3. THE STARE-MODE CONCEPT

For a stare-mode mission (with a single FOV) to be considered as a viable alternative to the scanning satellite concept, two basic issues need to be addressed and resolved:

1. Global astrometric accuracy from stitching together small overlapping fields, without the advantage of direct large-angle measurements (particularly for absolute parallax determination).

2. Overhead time (observing efficiency) for setting to the next field needs to be short, including the actual slew of the spacecraft, the settling time, guide star acquisition, and the detector readout time.

3.1. Global Astrometry with Block Adjustment Techniques

3.1.1. Traditional Ground-based Technique

The stare-mode idea presented here closely follows the traditional photographic astrometry survey principle. The telescope is pointed at a field of view, and all stars in the focal plane are integrated simultaneously while the pointing and field orientation angle are kept constant with the help of two or more guide stars. The FOV is then shifted, and the next field is exposed. Consecutive FOVs are overlapped by typically 25% to 50%. A zonal pattern of the sky is covered within a short period of time and is eventually supplemented by similar adjacent, overlapping observations to cover the entire sky.

This pattern of overlapping fields allows for a block adjustment (BA; Eichhorn 1960; de Vegt & Ebner 1974; Googe et al. 1970), in which the astrometric and instrumental parameters ("plate constants") are estimated at the same time in a single rigorous, nonlinear, least-squares adjustment. Any applicable reference star catalog is sufficient for an initial reduction of the data to get approximate starting values for the linearized BA procedure, which typically converges in a single

iteration step. The problem is rank deficient; an external orientation of the global coordinate system needs to be provided.[2] Usually, the best celestial reference frame available at the time is chosen for this external orientation in order for the new system to be consistent with the previous realization of such a system.

As an alternative to the BA reductions, it is possible to use an iterative conventional adjustment (ICA) scheme to perform the global reductions. A classical "single plate" adjustment gives improved positions for reference and selected field stars on a frame-by-frame basis. For individual stars, data are then combined to obtain mean position, proper motion, and parallax from all overlapping fields and from different epochs. These improved data are fed into the next iteration to repeat the adjustment. The ICA scheme converges to a consistent global catalog up to the accuracy limits of the input (x, y)-coordinates on a reference system that is represented by the average of all the original reference catalog star coordinates (external system orientation and rotation). The BA and ICA approaches give equivalent results (Benevides-Soares & Teixeira 1992). The BA approach is conceptually "cleaner" than the ICA but requires a huge amount of computer resources. In contrast to just the single-step classical "plate reduction," the BA and ICA concepts explicitly utilize the astrometric information (the same star on different exposures has only one set of astrometric parameters) from overlapping fields, involving all (suitable) stars in the reductions, not just the few reference stars.

The BA concept has been successfully applied in a few cases (Führmann 1979; Zacharias 1988) and has been studied with simulations (Zacharias 1992). It is important to realize that with a BA-type reduction, the scale and orientation (roll angle) parameters of each individual exposure are determined very precisely. If for some reason there is a jump in scale between exposures or a very small drift, it will not affect the astrometric results of the reductions. Scale and orientation, after all, represent very few parameters in a well-conditioned system of observation equations when dealing with many star images per exposure.

Although these applications have so far dealt with positions only, the formal extension of the principle and algorithm to include proper motions and parallaxes is straightforward. However, deriving *absolute* parallaxes and proper motions from small-angle measurements (ICA or BA) deserves some elaboration (see below).

3.1.2. Difference between SIM PlanetQuest and Astrograph-type Observations

The *SIM PlanetQuest* mission (Unwin & Shao 2000) has only a single field of regard (FOR); however, this FOR is relatively large (15°). Rigorous simulations (Makarov & Milman 2005) have shown that the mission goals for all five as-

trometric parameters (position, proper motion, and parallax) can be achieved, although the least-squares system is not well conditioned, at least if just stars are used for the astrometric grid, as originally planned. Recent simulations (Makarov et al. 2006) show that by including even a small number of extragalactic, fixed fiducial points (~25 QSOs), the absolute errors in parallax become significantly smaller (about factor of 2).

It is important to keep in mind that *SIM PlanetQuest* observations are fundamentally different from the astrograph-type mapping observations suggested here. *SIM PlanetQuest* does obtain (relatively) large-angle absolute measurements. However, *SIM PlanetQuest* observes only one-dimensional angular separations between two targets at a time, and a global grid must be stitched together by these quasi–absolute-angle measurements, including all instrumental parameters before any catalog of positions and motions can be established. A single astrograph-type observation yields differential two-dimensional positions for thousands of targets simultaneously, with a minimal number of instrumental parameters. Relative proper motions can be derived from astrograph-type observations of the same field at two or more different epochs, even without any overlap to adjacent fields (see, e.g., the Northern and Southern Proper Motion Surveys; Klemola et al. 1994; Platais et al. 1997).

3.1.3. Will the Stare-Mode Reductions Work for Global Astrometric Space Missions?

Block adjustment procedures in ground-based traditional photographic astrometry can be successfully applied even if there are very few reference objects (Zacharias 1992). The BA technique does not work very well for a zonal pattern (fields along a narrow strip around the sky) in the presence of systematic errors, but is well conditioned for a hemisphere or for all-sky coverage, due to the many inherent "closure conditions" (after going around the sky in a circle, the same stars are mapped, forcing the reduction solution to the same positions, give or take the effects of parallax and proper motion). A narrow zone has closure only along one axis, while the hemisphere or all-sky case is much "stiffer," with closures in two dimensions. Imagine a zone of few degrees' width around the equator. Coordinates along R.A. are well constrained, due to the closure at $0^h/24^h$ R.A. However, the star positions could easily have systematic errors along declination (for example, as a function of R.A.). With the entire hemisphere covered, there are multiple constraints reaching from one side, over the pole, to the other side to "fix" zonal errors.

Critical to the success of a BA or ICA approach, besides a hemisphere or all-sky coverage, are four issues:

1. Sufficient overlap between adjacent fields.
2. A sufficient number of link stars in overlapping frames.
3. Fiducial points for absolute parallax and proper motion determination.
4. High instrumental stability of *higher order* variations (mapping model).

---

[2] The same is true also for a scanning mission.

The first item is easily accommodated. The stare-mode operation allows for a flexible cadence to observe adjacent fields with overlaps as required.

The second item requires a large number of stars per unit area in the sky. This typically becomes feasible with a faint limiting magnitude of the instrument. For a *Hipparcos*-type mission, this actually would have been a problem, but it is not an issue for a *Gaia* or *OBSS* type mission. For a well-conditioned system, the mission precision σ_m (mean astrometric errors for a given target object, averaged over all observations of that target during the lifetime of the mission) will approach the limit $\sigma_m = \sigma_{smp}/\sqrt{n_t}$, given the single-measurement error σ_{smp} and the number of observations n_t per target (per coordinate).

Simulations with only a fourfold overlap pattern of a hemisphere using a small FOV of 4° and only about 200,000 stars lead to a well-conditioned system in which the actual σ_m is larger than the square-root-n limit by only about a factor of 1.04 (Zacharias 1992) for star positions.

Random errors of individual stellar position observations can lead to a zero-point offset of an entire field of about $\sigma_{smp}/\sqrt{n_s}$, where n_s is the number of (well exposed) stars in that field of view. If n_s is significantly larger than n_t, this zero-point offset of a field (i.e., zonal error) is likely to be smaller than the envisioned mean mission errors. In the example cases given below, this requirement is met and the BA reduction procedure will likely give the expected performance. Detailed simulations with the specific mission parameters for the *OBSS* case are planned for a phase A study.

The third requirement can be met by observations of quasars and compact galaxies. As soon as the limiting magnitude of the instrument can access a significant number of these extragalactic sources, they provide absolute reference points for parallaxes and proper motions. This concept is proven even for not much overlapping, differential, ground-based observations, for example by the Northern and Southern Proper Motion projects (Klemola et al. 1994; Platais et al. 1997). Again, this was not an option for *Hipparcos* but is not an issue for either *OBSS* or *Gaia*, which reach limiting magnitudes of 21 and 20, respectively. The zone of avoidance (i.e., the Galactic plane with high-extinction areas) is a comparatively small area in the sky for a global program, and the BA technique of linking all FOVs should be able to "bridge" those areas (pending further simulations to verify this assumption). Furthermore, some optical counterparts of quasars have been confirmed at very low Galactic latitudes (Zacharias & Zacharias 2005), and only a small number of fiducial points are required to set the zero-point for absolute parallaxes and proper motions.

The last item requires specific engineering in any case; one or two FOVs, and scanning or stare-mode observations. However, for the two-FOV, large-angle measurement approach, challenging basic-angle stability/monitoring requirements have to be added. The stare-mode option has the big advantage of being totally *differential*. Even a change in scale from one FOV to the next is easy to handle; only a few instrumental parameters, such as zero-point, scale, and orientation per FOV, contrast the large number of observations (individual [x, y] data of stellar images observed simultaneously) and the large number of overlap connections (adjacent fields, number of repeats of all-sky pattern). This leads to relatively low requirements on thermal gradients, etc., in the instrument design, with significant cost benefits compared to a quasi-absolute, large-angle measurement approach. The only requirement is that *higher order* mapping terms (field distortion pattern, etc.) be "calibrated out," and that a simple mapping model must describe the individual frames in the final BA (after an iteration and calibration). If too many parameters and changing calibration values over short periods of time are required, the global astrometry would suffer from significant error propagation losses.

3.2. Overhead

The stare-mode operation is potentially more inefficient than a spinning observatory that employs TDI-mode observing. There are two primary sources of inefficiency: first, during step-stare observing, the detectors must be read out. The readout period must be long enough to permit low read noise from the detector amplifiers and the readout electronics. If using standard CCD technology, no photons can be collected during readout, making the readout period essentially dead time in terms of integration. If, on the other hand, active pixel sensor (APS) detector technology such as CMOS or CMOS-hybrid sensors are used, pixels are read out while integration continues, eliminating this source of inefficiency. APS detector technology has the added benefit of supporting electronic shuttering, eliminating the need for a mechanical shutter.

The second source of overhead is the repositioning of the FOV after a field has been observed. During the repositioning of the FOV (and during any subsequent settling period of the structure), astrometric observations cannot be taken. The overhead can be minimized by overlapping the readout time with the reposition and settle time. However, it is important to remember that a scanning mission observes only one-dimensional data, while the stare-mode approach obtains two-dimensional data simultaneously, thus starting out with a factor of 2 advantage during the time of photon collection.

A somewhat lower efficiency is not necessarily a bad thing for astrometry if a higher astrometric quality (smaller systematic errors) is obtained. All dedicated astrometric instruments lose photons. *Hipparcos* utilized a modulating grid in the focal plane to observe one star at a time, disregarding all the other targets that would have been accessible simultaneously. Astrographs use narrow filters and sometimes grating images, reducing the limiting magnitude. Note that the spinning observatory loses efficiency in other places: unfavorable error propagation with one-dimensional observations when scans do

not intersect near orthogonal, and one-dimensional observations made one at a time.

Assuming an operation principle similar to that of the *Hubble Space Telescope*, which takes minutes to reposition to the next FOV, the stare-mode astrometric mission would not be an option. Current technology provides a couple of different solutions that lead to acceptable overhead times. For small apertures (≤0.5 m), one can envision a moveable, full-aperture scan mirror that, for example, rotates in half-degree increments so as to access a large arc (100° to 360°) for a step-stare instrument, without requiring reorientation of the observatory. Such an instrument has been discussed and appears feasible (K. Aaron 2005, private communication). As the aperture increases, however, the size and mass of the support structure and the method of moving the full-aperture, flat scanning mirror become increasingly problematic. At 1.5 m, a 45° inclination of the scan mirror with respect to the optical axis would result in a 2.2 m flat. This optical element must be properly stowed in the available fairing and deployed on-orbit, the torsional effects on the optical structure due to rotation of the mirror must be compensated for, and a nontrivial mechanism must be deployed in order to move the large flat. Moving the entire observatory seems more practical, at least for large-aperture stare-mode missions, and likely even for small apertures (Dorland & Zacharias 2005). This would not be feasible using reaction wheel technology, which has slew and settle times of an order of 100 s per field and a resulting observing efficiency of ∼10%. Control moment gyroscopes (CMGs), or constant-speed wheels, provide much higher torques, have a proven history in space, and are commercial, off-the-shelf items.

A dead time (no photon collection) of about 50% over the entire mission time can be considered as being very efficient compared to a scanning operation (see one-dimensional vs. two-dimensional observations above). The number of collected photons, leaving all other mission parameters the same, would be less in the stare-mode option, but the number of individual observations (stellar image coordinates) would be the same for both cases.

It should be noted that the stare-mode concept, with its constant readout and slew times, is naturally more efficient when taking long exposures. For example, a 100 s exposure with a 10 s overhead results in 90% observing efficiency. When combined with the fact that longer exposures using similar optics and detector performance result in a fainter noise floor, the stare-mode method of observing would appear to be more naturally suited to fewer, deeper exposures versus the scanning observing mode.

The loss due to overhead time in a stare-mode mission can be compensated for by increasing the size of the focal plane array (see also § 4), at the expense of a moderately reduced aperture. The stare mode can still go deeper (longer integration time) and is not restricted by the downlink rate (directed-beam antenna is possible), as was the case, for example, with the *FAME* mission concept. With selected field observing, which is possible if desired in stare mode, denser areas can be targeted more often, which dramatically enhances the ratio of observing stars to observing empty space.

3.3. Stare-Mode Operational Details

Operation of the envisioned stare-mode astrometric mission would take place as follows: The telescope slews to a new field, locks onto at least two guide stars, settles, and starts tracking. Then the longer of two exposures begins, followed by a readout of the detector array, while the pointing of the telescope is still fixed and the guide trackers are running. The second, shorter exposure is taken. While the detector array reads out again, the guiders are disengaged and the telescope moves to the next, adjacent field.

The two exposure times of different duration (e.g., a factor of 10) allow coverage of a large dynamic range and are also good astrometric practice to check on possible magnitude-dependent systematic errors. More than two exposures per pointing can be observed if required (e.g., with different filters) if a design including refractive elements is favored.

Onboard processing would include the raw data processing (bias and flat-field corrections), as well as object detection. The expected cosmic-ray environment may necessitate onboard first-order cosmic-ray–rejection logic. Pixel data from small subareas around each detected object are saved, compressed, and eventually relayed to the ground, together with instrumental parameters and information about field position in the sky, time, and integration time.

In order to apply the BA or ICA reduction techniques, adjacent fields need to be observed, with significant overlap in sky area. In order to solve for parallax and proper motion, several all-sky observations need to be completed each year. Examples (see below) show that neither requirement poses a problem.

The actual observing cadence can be very flexible; for example, longer integration times and more data can be taken in selected areas of scientific interest or for faint targets. Spending on the order of a few hours of observing time on a small area in the sky could result in quasi–single-epoch mean positions on the microarcsecond precision level (see the 1.5 m telescope example in § 5). Another option is to observe specific fields very often throughout the mission, for good temporal sampling. The general all-sky survey can be made to be uniform if desired, with the same number of observations per field all over the sky.

A mix of an all-sky survey and targeted observing mode is likely to give extraordinary scientific return (Johnston et al. 2005, 2006). Part of the total observing time is spent on an all-sky survey spread over the entire mission lifetime in order to be able to solve for absolute parallax and proper motion with high accuracy. The remaining observing time is allocated

TABLE 1
BASIC INPUT PARAMETERS FOR THE ASTROMETRIC MISSION
PRECISION ANALYSIS

Item Description	Symbol	Unit
Number of exposures per pointing ………	n_{ex}	…
Mean exposure time, single exposure ……	t_{ex}	Second
Overhead time per pointing ……………	t_{ov}	Second
Total mission time ………………………	T	Year
Single-measurement precision …………	σ_{smp}	Pixel
Aperture …………………………………	a	Meter
Focal length ……………………………	f	Meter
Sampling ………………………………	S	Pixel per FWHM
Diameter of focal plane …………………	d	Meter
Central wavelength ……………………	λ	Nanometer

to specific target areas, with observing cadence and limiting magnitude tailored to specific science goals.

4. MISSION PRECISION

4.1. Definitions and Assumptions

How good can a stare-mode astrometric mission be? In the following discussion, the "best mission precision" σ_m is derived from some basic mission parameters and assumptions. In general, astrometric precision will depend on the brightness of the stars. For saturated, overexposed stars, no high-precision results are assumed, while for faint stars, the precision also drops, due to the low signal-to-noise ratio (S/N). Thus, the best astrometric precision is achieved for stars near but just below the saturation limit. The width of this "sweet spot" depends on how much the overall error is dominated by just the S/N or other errors (see below).

The following assumptions are made:

1. The location for the best astrometry "sweet spot" on the magnitude scale is not forced to a particular value. There is no requirement for a certain positional error at a certain magnitude. The results obtained below will need to be shifted to a desired magnitude interval, due to additional considerations. In particular, a sufficient number of overlap stars need to be available, which excludes scaling to very small apertures and low limiting magnitudes with a small field of view (see examples and discussion below). The goal here is to find the smallest astrometric error overall, regardless of the magnitude at which this occurs.

2. Mainly random errors are considered; thus, we deal with precision, not accuracy. However, to be realistic, a base level of systematic error is assumed for the single-measurement precision, independent of photon statistics.

3. A well-conditioned system with nearly no "loss" due to error propagation is assumed. Thus, the mean precision of a star position after a completed mission follows the square-root-n law.

4.2. Calculations

For the purpose at hand, let the instrument and mission be defined by the set of basic input parameters given in Table 1. In particular, the single-measurement precision σ_{smp} is the assumed error floor, a combination of random and systematic errors on the individual stellar image centroiding level, given as a fraction of a pixel. The value of σ_{smp} will depend on the astrometric quality of the hardware and thus be different from case to case as a function of many technical details of the telescope, detector, and operations. In the examples in § 5 below, realistic values are introduced for this free parameter. Astrometric quality is explained in more detail in a design study of the USNO Robotic Astrometric Telescope (Zacharias et al. 2006). Furthermore, in the algorithm that follows, a circular aperture and focal plane is assumed; however, any shape leads to the same conclusions.

Table 2 summarizes the quantities derived from the set of basic parameters, and it also shows the equations and units that are used. The goal is to arrive at the overall mission precision σ_m for a single stellar position coordinate of a star within the "sweet spot" of brightness.

TABLE 2
DERIVED PARAMETERS CHARACTERIZING A STARE-MODE MISSION

Item Description	Dependence
Resolution (mas) ……………………………	$r = 1.22\lambda\ 0.206265/a$
FWHM of image profiles (mas) ……………	FWHM $\approx 1.0r$
Image scale (arcsec mm^{-1} = mas μm^{-1}) ……	$s = 206.265/f$
Diameter of field of view (deg) ……………	FOV $= ds(1000/3600)$
Pixel scale (mas pixel^{-1}) ……………………	$p_s =$ FWHM$/S$
Linear pixel size (μm) ………………………	$p_x = p_s/s$
Integration time per pointing (s) …………	$t_i = n_{ex}t_{ex}$
Time spent at one pointing (s) ……………	$t_p = t_i + t_{ov}$
Total number of single observations ………	$n_{tot} = n_{ex}86,400\ 365.25T/t_p$
Sky area per pointing (square deg) …………	$A \approx 0.7$ FOV^2
Time for one sky coverage (day) …………	$t_s = (41,000/A)t_p/86,400$
Observing frequency (visits yr^{-1}) ………	$\nu = 365.25/t_s$
Number of single observations per star ……	$n = T\nu n_{ex}$
Angular single-measurement error (mas) ……	$\sigma_1 = \sigma_{smp}\,p_s$
Mission precision (mas) ……………………	$\sigma_m = \sigma_1/\sqrt{n}$

Using the algorithm of Table 2, quantities are then back-substituted into the mission precision σ_m equation to allow only basic input parameters (Table 1). Dropping all numerical scale factors (and some unit conversion factors) gives the following proportionality equations:

$$n = T\nu n_{\text{ex}},$$

$$\approx \frac{Tn_{\text{ex}}A}{t_p},$$

$$\approx \frac{Tn_{\text{ex}}d^2 s^2}{t_p},$$

$$\approx \frac{Tn_{\text{ex}}}{t_p}\left(\frac{d}{f}\right)^2,$$

$$\sigma_m \approx \sigma_{\text{smp}} \frac{p_s}{\sqrt{n}},$$

$$\approx \sigma_{\text{smp}} \frac{\text{FWHM}}{S} \sqrt{\frac{t_p}{Tn_{\text{ex}}}} \left(\frac{f}{d}\right),$$

$$\approx \sigma_{\text{smp}} \sqrt{\frac{t_p}{Tn_{\text{ex}}}} \left(\frac{f}{dS}\right)\left(\frac{\lambda}{a}\right).$$

This is the best astrometry ("sweet spot") achievable as a function of the basic parameters as defined above. A few newly defined key items simplify this equation. Using the total number of exposures $n_{\text{tot}} = n_{\text{ex}}T/t_p$ and the linear pixel size $p_x \approx \lambda f/aS$, we have

$$\sigma_m \approx \sigma_{\text{smp}} \sqrt{\frac{1}{n_{\text{tot}}}} \left(\frac{p_x}{d}\right).$$

The product of σ_{smp} and p_x is nothing more than the single-measurement precision expressed in linear units (μm), which we call σ_{sml}; thus,

$$\sigma_m \approx \frac{\sigma_{\text{sml}}}{d} \sqrt{\frac{1}{n_{\text{tot}}}}.$$

4.3. Discussion

From the above assumptions and the result for the best achievable astrometric mission precision σ_m for the stare-mode concept, we find the following:

1. The value for σ_m does *not* depend on the aperture of the telescope, nor the focal length, nor the sampling. If we want to shift the "sweet spot" to a required magnitude, this of course

needs to be accomplished by a certain combination of aperture, exposure time, throughput (bandwidth, quantum efficiency, etc.), and mission lifetime. However, the numeric value for the best astrometry remains unaffected by shifting it to a desired magnitude; thus, it is independent of aperture, focal length, bandwidth, and quantum efficiency (QE).

2. The value for σ_m does not depend on wavelength. Thus, we are free to choose the spectral regime we want the mission to operate in. The choice of a specific wavelength will require a match between the focal length and pixel size, with the desired sampling. This will not affect σ_m. However, manufacturability and alignment tolerances are better suited for red than for blue spectral bandpasses. For a given linear tolerance (fixed cost), the wave-front error as a fraction of the wavelength is smaller for a red than for a blue light, which buys an advantage in image quality.

3. The value for σ_m does not depend on the pixel size directly. However, it does depend on the product of pixel fraction error and pixel size; i.e., it depends directly on the linear measurement precision in the focal plane. For very small pixels, the limiting factor will be the physical structures in the pixels, while for very large pixels, the limiting factor will be the pixel fraction for the image centroiding. It is important to minimize σ_{sml}.

4. The driving factors toward smaller σ_m are a large number of single measurements and a large focal plane. The large number of measurements (with a constant mission lifetime) implies numerous short exposures, with minimal overhead. This is somewhat contrary to the basic mission concept and is particularly at odds with a requirement of having many visits, as for example for the science goals of detecting many exoplanets. However, a very large number of observations then heavily relies on the $\sqrt{n}$ law, which fails at some point, due to systematic errors.

5. The biggest and easiest way to impact σ_m can be achieved by increasing the linear size of the focal plane. Smaller astrometric errors can be obtained by focusing expenses on the focal plane rather than the aperture of the telescope optics. For sampling near critical ($\sim$2 pixel FWHM) and for visible to near-infrared wavelengths, the f-ratio of the optical system will be slow (about f/30). This is an advantage for an optics design. The focal length and the angular size of the field of view will only affect the number of visits, not σ_m directly.

5. EXAMPLES

Table 3 gives numerical values for two example stare-mode missions: a large-aperture mission, such as the current *OBSS* baseline, and a small, feasibility-study–type mission, such as the *Milliarcsecond Pathfinder Survey* (*MAPS*) satellite currently under study at the US Naval Observatory (Dorland & Zacharias 2005; Dorland et al. 2005). *MAPS* will also be a technology demonstration mission, using a single large-format CMOS or CMOS-hybrid detector. Even the small *MAPS* mis-

TABLE 3
EXAMPLE MISSIONS: 1.5 m APERTURE *OBSS* AND
SMALL TEST SATELLITE (*MAPS*)

Item	OBSS	MAPS[a]
Number of exposures per pointing	2	2
Total overhead time per pointing (s)	20.0	10.0
Size of single CCD, linear (mm)	50.0	80.0
Total mission time (yr)	5.0	2.5
Single-measurement precision (μm)	0.050	0.100
Fraction of gaps between CCDs	0.150	0.000
Aperture size (m)	1.50	0.15
Pixel size (μm)	10.0	10.0
Sampling (pixel FWHM)	2.5	2.0
Number of CCDs	360	1
Long-exposure time (s)	20.0	15.0
Short-exposure time (s)	2.0	5.0
Central wavelength (nm)	600.0	650.0
Overall (system) QE (fraction)	0.60	0.60
Width of bandpass (nm)	300.0	200.0
Read noise (e^-)	7.0	15.0
Total number of pixels (gigapixels)	9.00	0.06
Resolution, 1.22 λ /aperture size (mas)	100.7	1090.5
FWHM profile = 1.0 resolution (mas)	100.7	1090.5
Pixel scale (mas pixel^{-1})	40.3	545.2
Scale (mas μm^{-1})	4.03	54.52
Focal length (m)	51.23	3.78
f-number aperture/focal length	34.2	25.2
Focal plane area pixel coverage (m^2)	0.900	0.006
Focal plane diameter (m)	1.15	0.09
Diameter FOV (deg)	1.28	1.37
Total integration time per pointing (s)	22.0	20.0
Sky area per pointing (square deg)	1.43	1.87
Time for all sky once (day)	13.9	7.6
Observation frequency (visits yr^{-1})	26.3	48.0
Total number of single observations per star	262.7	239.8
Best single-measurement error (mas)	0.201	5.452
Best single-measurement error (1 pixel^{-1})	200.0	100.0
Square-root-*n*, best mission precision (μas)	12.4	352.1
Square-root-*n* at limiting magnitude (μas)	351.0	4980.0
Full well capacity (ke^-)	123.0	123.0
Limiting magnitude, short exposure (mag)	18.4	14.0
Limiting magnitude, long exposure (mag)	20.9	15.2
Saturation magnitude, short exposure (mag)	11.6	7.6
Saturation magnitude, long exposure (mag)	14.4	8.7
Faint limit, best astrometry (mag)	15.4	11.0
Range of magnitudes, best astrometry (mag)	1.0	2.3
CMOS saturation, short exposure (mag)	8.6	4.6
CMOS saturation, long exposure (mag)	11.4	5.7
CMOS range, best astrometry (mag)	4.0	5.3

[a] The bright star limit of *MAPS* will be about 3rd magnitude, due to a special observing mode with multiple very short integrations on bright targets. This table is simplified for direct comparison with *OBSS* and does not reflect that option.

sion would be capable of improvements over *Hipparcos*, including a factor of about 3 gain in positional precision, and a factor of 100 increase in the number of stars. The *MAPS*-like example given in Table 3 gives about 250 μas mission precision for a single well-exposed star, while the stated *MAPS* goal is to achieve at least 1 mas accuracy. For the *MAPS* mission, the required extragalactic targets would be near the limiting mag-

nitude of the general all-sky survey, with an unfavorable S/N. However, the flexibility of the stare-mode concept would permit more observations of the required number of relatively faint targets, and with longer integration times.

The magnitudes at the bottom of Table 3 for the CMOS case assume that high-precision stellar image centroids can be obtained for stars up to 3.0 mag brighter than the saturation limit. No charge bleeding will be present, and such bright stellar images can be fitted using the unsaturated wings of the profile. This is a conservative estimate; good astrometric results might be obtained for even brighter stars. The astrometric quality of such centroids will at some point be limited by the optical quality of the observed point-spread function on the 1% level of the peak intensity and below, by stray light, and by other factors if a stellar image is vastly overexposed, even if the detector does not bleed at all.

Results expected from the large *OBSS*-type mission are comparable to *Gaia*, with the additional benefit of being able to reach fainter stars in a general all-sky survey and going significantly deeper for targeted fields. For a comprehensive discussion of *OBSS* capabilities and science goals, see the NASA road map report by the US Naval Observatory (Johnston et al. 2004), which also mentions other issues of concern, together with suggested solutions. The shutter issue, the required quality of the guiding, CPU power requirements, the downlink rate, and several other issues of possible concern are identified as not being intractable problems.

Systematic errors will likely limit the performance of any astrometric mission. Comparisons of the two-FOV, large-angle measurement approach and the single-FOV, differential mode show that both have to cope with imperfections of the optics and image centroiding issues. Imperfect knowledge of field distortions, shifts of centroid positions as a function of magnitude, and colors of the stars will affect both types of missions similarly as they perform accurate differential measurements in the focal plane. A scanning mission might have some advantage, because the signal for each observation is averaged over many pixels. The two-FOV approach has the disadvantage of having absolute large-angle measurements, which have the basic angle stability problem, a possible source of significant additional systematic errors.

6. CONCLUSIONS

For a *Hipparcos*-type mission, the scanning operation concept was a good choice. Without access to a sufficient number of extragalactic targets, large-angle measurements (two fields of view separated by an order of 90°) are essential to obtain absolute parallaxes. Even today, if an astrometric mission were limited to 12th magnitude, a *Hipparcos*-type concept would be the way to go. For a mission that is capable of accessing extragalactic sources and can move between fields quickly relative to the integration time, the stare-mode concept has become a viable alternative to the traditional two-FOV scan-

ning operation. Both conditions are met for the stare-mode missions now under consideration (*OBSS* and *MAPS*). For these missions, a two-FOV scanning concept would still have the advantage of many individual observations, which is important for some science goals, such as detecting extrasolar planets. The achievable astrometric mission precisions are comparable between the scanning and stare-mode concepts if the large square-root-*n* factor for a scanning mission can be accepted as the mission accuracy estimate. However, the stare-mode concept is a lower risk approach with a high single-measurement precision, a more conservative square-root-*n* factor, and simpler engineering requirements (and thus lower costs). It has the advantage that no technological developments are needed.

The major advantages of a stare-mode astrometric mission are the high degree of flexibility, the higher astrometric precision in targeted areas, the ability to go significantly deeper, and the reduced complexity of the hardware, with easier-to-achieve engineering requirements. The stare-mode concept also potentially allows the use of radiation-hard CMOS detectors, which have an inherent large dynamic range (no blooming) and thus would also allow low-risk access to relatively bright stars, particularly in combination with short exposure times. Exposure times in general are unrestricted in stare-mode operations, contrary to the scanning mode of operation.

At this time, the stare-mode concept is not nearly as well developed as the scanning satellite concept, and detailed simulations will soon be performed to better understand the exact requirements, capabilities, and limitations. A particularly appealing aspect of a stare-mode mission such as *OBSS* is that it has the ability to be a complementary or replacement mission, depending on the observing schedule, but using the same hardware. If *Gaia* performs as predicted, a stare-mode mission could take the *Gaia* reference frame and concentrate on deep, targeted fields. If *Gaia* does not perform as currently envisioned, the stare-mode mission could independently fulfill most of *Gaia*'s science goals in a mainly general all-sky survey. Furthermore, because the design is fundamentally different than that of *Gaia*, it offers redundancy in case there are problems in *Gaia*'s implementation. A large enough stare-mode mission could also substitute for much of the *SIM PlanetQuest* targeted mission science. In order to get a real proof of concept, a small feasibility-study–type mission such as *MAPS* is strongly suggested, which could have a fast turnaround time and give valuable insight for the planning of a full-scale mission.

REFERENCES

Benevides-Soares, P., & Teixeira, R. 1992, A&A, 253, 307

de Vegt, Chr., & Ebner, H. 1974, MNRAS, 167, 169

Dorland, B., & Zacharias, N. 2005, *MAPS* concept study (Washington: US Naval Obs.)

Dorland, B., Zacharias, N., Gaume, R., Johnston, K., Hennessy, G., Makarov, V., & Rollins, C. 2005, BAAS, 37, 1196

Eichhorn, H. 1960, Astron. Nachr., 285, 233

ESA. 1997, The *Hipparcos* Catalogue (ESA SP-1200; Noordwijk: ESA)

———. 2000, *Gaia*: Composition, Formation and Evolution of the Galaxy, Concept and Technology Study Report (ESA-SCI(2000)4; Noordwijk: ESA)

Führmann, U. 1979, Ph.D. thesis, Univ. Hamburg

Gaume, R. A., & Johnston, K. J. 2003, BAAS, 35, 1206

Googe, W. D., Eichhorn, H., & Lukac, C. F. 1970, MNRAS, 150, 35

Johnston, K. J. 2003, Proc. SPIE, 4854, 303

Johnston, K. J., et al. 2004, BAAS, 36, 1342

———. 2005, The *Origins Billions Star Survey*, NASA Roadmap Study (Washington: US Naval Obs.)

———. 2006, PASP, 118, 1428

Klemola, A. R., Hanson, R. B., & Jones, B. F. 1994, in Galactic and Solar System Optical Astrometry, ed. L. V. Morrison & G. F. Gilmore (Cambridge: Cambridge Univ. Press), 20

Lacroute, P. 1982, in Proc. Int. Colloq., The Scientific Aspects of the *Hipparcos* Space Astrometry Mission, ed. M. A. C. Perryman & T. D. Guyenne (ESA SP-177; Noordwijk: ESA), 3

Makarov, V. V., Johnston, K. J., & Zacharias, N. 2006, BAAS, in press

Makarov, V. V., & Milman, M. 2005, PASP, 117, 757

Platais, I., et al. 1997, in Proc. ESA Symp. *Hipparcos* Venice '97, ed. B. Battrick (ESA SP-402; Noordwijk: ESA), 153

Röser, S. 1999, in ASP Conf. Ser. 194, Working on the Fringe, ed. S. Unwin & R. Stachnik (San Francisco: ASP), 68

Unwin, S. C., & Shao, M. 2000, Proc. SPIE, 4006, 754

van de Kamp, P. 1967, Principles of Astrometry (San Francisco: Freeman,)

Zacharias, M. I., & Zacharias, N. 2005, in ASP Conf. Ser. 338, Astrometry in the Age of the Next Generation of Large Telescopes, ed. P. K. Seidelman & A. Monet (San Francisco: ASP), 184

Zacharias, N. 1988, in IAU Symp. 133, Rigorous Block-Adjustment of the CPC2 Cape Zone, ed. S. Debarbat (Dordrecht: Kluwer), 201

———. 1992, A&A, 264, 296

Zacharias, N., Laux, U., Rakich, A., & Epps, H. 2006, Proc. SPIE, 6267